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AN INVESTIGATIVE REVIEW AND EXPERIMENTAL APPROACH FOR THE PERFORMANCE ASSESSMENT OF SMALL SCALE GIFFORD-MCMAHON CRYOCOOLER

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ABSTRACT

Helium recondensation or liquefaction system is the best platform to liquefy or to condense the helium in many applications viz., Nuclear Magnetic Resonance (NMR), Magnetic Resonance Imaging (MRI) and Superconducting Quantum Interference Devices (SQUIDS). These applications make use of liquid helium as a refrigerator. The large scale liquefaction systems serve as a central facility to provide liquid helium. The above mentioned applications require refilling on a regular basis which is troublesome in case of large scale liquefaction system; one can make use of small scale liquefaction setup based on a cryocooler. An effort has been made to develop a small scale liquefaction system by using two-stage Gifford McMahon cryocooler. This investigative review paper illustrates the liquefaction of helium by using a commercial cryocooler with 1.5 W cooling power at 4.2 K, provided with facility to precooling of incoming gas by using special type of heat exchangers.

KEYWORDS: Recondensation, Liquefaction, Heat Exchanger, Cryocooler & Cooling Power

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Original Article

1. INTRODUCTION

Liquid helium is obtained by cooling helium gas to 4 K or -269^{0}C. Many laboratories around the world require liquid helium as working medium for low temperature experimentation. In current scenario, liquid helium generating systems are expensive and greatly compatible. The maintenance and operation of the helium liquefier involve considerable efforts. However, there are a number of applications viz. Nuclear Magnetic Resonance (NMR), Magnetic Resonance Imaging (MRI), and Superconducting Quantum Interference Devices (SQUIDS). The mentioned applications require liquid helium on a regular basis and in medium amount for its functioning. In the absence of such a large scale helium liquefaction system, the regular basis of filling liquid helium is not an only cumbersome task but also expensive. The best alternative to produce liquid helium in medium amounts and in regular basis is by using a Gifford-McMahon (GM) based helium liquefaction system [1, 2].

The general liquefaction of gas can be achieved by two thermodynamic processes: firstly isothermal compression process followed by an adiabatic expansion process. In the first process, at constant temperature the gas is compressed to high pressure with the help of suitable mechanism. In the second process, the gas at high pressure is permitted to expand in the adiabatic condition, in which neither the heat energy is permitted to enter or exit from the system. Because of these processes, it is possible to observe a drop in temperature as the pressure is inversely proportional to temperature. The processes are repeated until gas liquefies. The expansion will be of

either isentropic or isenthalpic. Usually Joule-Thomson expansion results in an isenthalpic expansion and a reciprocating engine or turbine expansion results in an isentropic expansion. Normally the helium gas liquefaction is carried out by the conventional Linde and Claude's processes. In Linde method, air is cooled, compressed and expanded in an alternate manner and the expansion process results in a lowering of temperature each time [3, 4].

In 1872, Carl von Linde liquefied air by using Joule-Thomson (JT) principle. Sir Louis Paul Cailletet, a French mining engineer produced oxygen fog in 1877 by compressing to 300 atmospheres. In the same year, a Swiss physicist produced liquid oxygen by using cascade system. In 1883, the two cryogenisists, Szygmunt Von Wroblewski and K. Olszewski first liquefied nitrogen and oxygen at a laboratory in Cracow University. They were successful in condensing gases; because of heat load coming from ambient condition they were unable to store them in liquid form. Sir James Dewar of London at Royal Institution solved this problem. He discovered a vacuum environment (the environment which has the least number of molecules) to store cryogen liquid.

McMahon and W. E. Gifford introduced a new system of refrigeration in 1959 for creating small cryogenic refrigerators. The thermodynamic cycle was referred to as Gifford-McMahon cycle. The main reason for using this cycle is its ease of construction, practicality and reliability. The refrigerator system which operates on this cycle is known as Gifford-McMahon cryocooler. This refrigerator system is used for small scale liquefaction of Helium and Nitrogen gasses in MRI scanners for cooling of radiation shield and in superconducting magnetic systems. It is a smaller system and efficiently handles the heat load coming from atmospheric condition to liquid helium. Longsworth and Gifford introduced a pulse tube cryocooler in mid 1960s. Phenomenal growth has been achieved in past two decade by incorporating a buffer volume through an orifice volume at warm side of pulse tube resulting in enhanced cooling performance.

Chao Wang of cryomech Inc. filed a patent on gas liquefaction in 2007 and was permitted in 2009 to use a pulse tube refrigerator by placing its cold head inside the neck of Dewar to liquefy the gases impending into Dewar. It was invented in order to support the laboratories working with liquid helium because most of helium liquefiers of larger size and not applicable to small laboratories [5, 6].

The primary advantages of GM cryocooler are, it has greater reliability and lower cost. The GM cycle cryocooler has the advantage of being greater thermodynamic efficiency. The major advantages of the GM cryocooler are they are available commercially from a large number of manufacturers in several different sizes, both in single stage and two stage versions. Good service is usually available for replacing the displacer seals and for other problems associated with GM cryocooler. The flexible gas lines are equipped with quickly connects self-healing to allow them to be disconnected from the system without losing helium gas or letting in air.

In the present scenario, researchers and scientists are fascinated in exploring new developments pertaining to liquefaction systems. They have carried out an extensive research work on different cryogenic refrigeration because of their admirable cryogenic properties. The performance analysis of liquefaction systems have been a demanding and challenging task for the researchers. Helium liquefaction systems are more promising cryogenic systems and data pertaining to cryogenic properties have to be established. This aspect has generated enormous interest in research pertaining to the area of cryogenic liquefaction and refrigeration. Hence, emphasis needs to be given to carry out research on cryogenic characterization and analysis of liquefaction systems. This research work intends to enhance the comprehension of the cryogenic aspects of Helium liquefaction by using two-stage GM cryocooler, thus emphasizing the scientific novelty and technological relevance.

The objectives of this section are to furnish a review of the past research efforts related to the cyrogenic characterization and analysis of liquefaction systems. In this literature review, cryogenic techniques, thermal behaviour of liquefaction systems, use of various cryogenic Analyzers and numerical thermal analysis have been studied. In the literature review, importance has been given for the performance assessment of cryogenic and liquefaction systems. Also, numerical analysis of cryogenic systems based on finite element approach has been discussed. The challenges in research and the definite directions relating to this research work have been identified through a detailed literature review. The papers concerning cryogenic characterization and analysis of liquefaction systems have been discussed in this section.

After the introduction of the pulse tube cooler by Gifford and Longsworth in the mid 1960s, numerous improvements of this refrigerator type have been achieved in the past decade by two types of modifications: adding a buffer volume via an orifice valve to the warm end of the pulse tube led to phase shift between pressure and velocity with resulting improvements in cooling performance.

In 1998, Thummes and his associates reported that the liquefaction rate of 127 ml/h obtained for a pulse tube cooler with 170 mW net cooling power at 4.2 K. A temperature of 3.6 K and a net cooling power of 30 mW at 4.2 K were first obtained with a three-stage pulse tube cooler by Matsubara. A regenerative tube at the warm end of the third stage pulse tube was used in their system. They obtained a lowest temperature of 2.75 K. Thummes achieved the lowest temperature of 2.75 K by using a two-stage pulse tube cooler and the process and performance of two configurations of 4 K pulse tube coolers and GM cryocoolers by C. Wang in 1997. C. Wang, G. Thummes and C. Heiden investigated a two-stage double-inlet pulse tube cooler in 1996 for cooling below 4 K is designed and constructed by numerical analysis. The hot end of the second stage pulse tube was connected to the phase shifting assembly at room temperature without the use of a regenerative tube. A research paper by P. Schmidt-Wellenburg explains that the helium liquefaction by using a commercial cryocooler with 1.5 W cooling power at 4.2 K along with heat exchangers for cooling of incoming gas. They acquired a net liquefaction rate of 55.7g/h at one bar pressure.

Tallaki Morie et al. [7] have illustrated that, 4K GM cryocoolers are inevitably exposed to the magnetic field in MRI systems. The cooling capacity of a 4K GM cryocooler is strongly dependent on the heat capacity of the magnetic regenerator materials, such as $HoCu_2$, Er_3Ni and Gd_2O_2S(GOS). In order to clarify the effect of the magnetic field on acryocooler's performance, we measured the cooling capacity of Sumitomo Heavy Industries, Ltd. (SHI) 1W 4K GM cryocoolers in magnetic fields up to 2.0 T. It is found that the impact of a magnetic field on the cooling capacity with a $HoCu_2$/GOS hybrid regenerator is much smaller than that with a $HoCu_2$ regenerator.

T Satoh et al. [8] have explored a Gifford-McMahon cryocooler operating below 2K. According to the proposed theory, a Gifford-McMahon (GM) cycle cryocooler with ^{4}He cannot cool below 2 K because of the ^{4}He super fluid transition near this temperature. However replacing ^{4}He by ^{3}He removes this temperature limitation. The cooling performance of a GM cryocooler with a **$HoCu_2$** magnetic regenerator material is investigated using ^{3}He. The minimum temperature of 2.3 K with ^{4}He goes down to 1.65 K when the ^{4}He working fluid is replaced by ^{3}He. The maximum cooling capacity at 2 K is 53.9 mW with a compressor power of about 2.5 kW, and the cooling capacity at 4.2 K is enhanced by more than 20%. The effect of a new regenerator material **($NdInCu_2$)** on the cooling performance was also investigated. The minimum temperature decreased to 1.64 K and the cooling capacity at 2 K improved to 57.1 mW with the use of this material in the bottom 40% of the regenerator.

T. Satoh et al. [9] have developed 1.5 W 4K GM cryocooler with a magnetic regenerator material. A two-stage 4K Gifford-McMahon (GM) cycle cryocooler with magnetic regenerator material which has cooling capacity 1.5W at 4.2K has been developed. The hybrid structural second regenerator composed of lead and $ErNi_{0.9}Co_{0.1}$ was used in the cryocooler. $ErNi_{0.9}Co_{0.1}$ has a large specific heat peak at lower temperature than 10K and lead has a larger specific heat in the high temperature region. The intake/exhaust valve timing was optimized to improve the cooling capacity not only of the second stage but also of the first stage. A larger size second cylinder in diameter than the former one was used to get a larger pressure-volume (PV) work.

I. Takashi et al. [10] have developed a 2W class 4K Gifford-McMahon cycle cryocooler. This paper describes the principal design features and performance of the Gifford-McMahon cycle cryocooler by which they could obtain a cooling capacity of 2.2W at 4.2K. The main features of this machine are its large size expansion space, its use of rectifiable meshes which are packed in a regenerator at equal intervals, and its use of the combination of Er_3Ni and $ErNi_{0.9}Co_{0.1}$ as regenerator materials.

M. Xuet al. [11] have developed a compact 2K GM cryocoolers. A compact 2K Gifford-McMahon (GM) cryocooler has been developed for cooling electronic devices, viz., Superconducting Single Photo Detectors (SSPD). The heat exchangers, regenerators are optimized with the numerical simulation method developed for 4K GM cryocoolers. After optimizing, the cylinder length has been reduced by 85 mm compared with a commercial 0.1W 4K GM cryocooler. With no load on the second stage, a temperature of about 2.1 K has been achieved. With 1 W and 20 mW heat load, the temperature is 44.4 K at the first stage and 2.23 K at the second stage with an input power of about 1.1 kW. And also, it is found that the temperature oscillation decreases as the average temperature decreases. A temperature oscillation of about ±20 mK has been achieved.

Dong Xu et al. [12] showed that 4.2 K could be used to re-liquefy evaporated helium gas of small sized and medium sized cryogenic devices. A sequence parallel path helium liquefier with a liquefaction rate of 83 liters per day (l/day) using five 4 K GM cryocoolers is developed, and has been applied to Wuhan National High Magnetic Field Center (WHMFC) in China.

P. L. Kapitza [13] described an expansion engine which works without any lubrication at very low temperatures, and accounting its use in liquefaction of helium. Only liquid nitrogen has been used to precool the liquefier, and two stages involved in further cooling down to 10 K with the help of the expansion engine, and finally achieving liquefaction by Joule-Thomson effect.

R. Kneuer [14]explains about a multi-range helium liquefaction plant, designed for automatic constant state operation is described by them. During cool down data are given for its operation, steady-state liquefaction and refrigeration takes place under certain conditions.

Akihiro Nakano [15] manufactured a small-scale hydrogen liquefier with the help of two-stage 10 K GM cycle refrigerator. It contains a hydrogen tank with the storage volume of 30 liters that was encapsulated by a shield of radiation. This liquefier continuously liquefies gaseous hydrogen with the volumetric flow rate 12.1 nanoliters/min. It accounts to the liquefaction rate of 19.9 liters/day for liquid hydrogen. They also proposed a simple estimation method for the liquefaction rate and the estimation method well matches with the liquefaction rate of experimentation.

T. B. He and Y. L. Ju[16] demonstrated Liquefaction of natural gas (LNG), which is usually a process of high energy consumption. Therefore, any performance advancement of the liquefaction process will result in reducing the energy consumption. Liquefaction process using nitrogen expansion is taken as a suitable process for small-scale LNG plant due to its quick startup, simplicity and easy maintenance. However, the demerit of this process is high-energy consumption. An efficient way to reduce its energy consumption is to include a precooling cycle. In this paper, they showed two different precooling cycles counting propane precooling cycle and R410a precooling cycle are recommended to the nitrogen expansion liquefaction process to upgrade the liquefaction process performance.

P. Schmidt-Wellenburg and O. Zimmer [17] have illustrated helium liquefaction by using a commercial cryocooler with 1.5 W cooling power at 4.2 K (Sumitomo model RDK415D with compressor CSW-71D, consuming 6.5 kW electrical power), equipped with heat exchangers for precooling the incoming gas. No additional cooling power of cryoliquids or additional Joule-Thomson stages was utilized. Measurements of the pressure dependence of the liquefaction rate were performed. A maximum value of 83.9 g/h was obtained for 2.25 bar stabilized input pressure. Including the time needed to cool the liquefied helium to 4.2 K at 1 bar after filling the bottle connected to the cold head, and correcting for heat screen influences, this results in a net liquefaction rate of 67.7 g/h. Maintaining a pressure close to 1 bar above the bath during liquefaction, a rate of 55.7 g/h was obtained. The simple design enables many applications of the apparatus.

It is evident from the literature review that, the performance assessment of Gifford-McMahon cryocooler has been given greater emphasis. However, investigations concerning the liquefaction of Helium by using 1.5 W cooling power at 4.2 K is meagre. Many experimental investigations have been carried out based on other liquefaction systems, but limited work has been accomplished pertaining to 1.5 W cooling power at 4.2 K. The literature review has indicated the need for further investigations on Helium liquefaction by using GM cryocooler. If these liquefaction systems are to be used for many engineering applications, the cryogenic aspects need to be given more emphasis. Hence it becomes important that the evaluation of cryogenic aspects and characteristics of liquefaction systems cannot be ignored in order to transform the material from design stage to manufacturing stage. This would provide the researchers a sense of continuity and help them pacing their research.

2. EXPERIMENTION FOR LIQUID HELIUM PRODUCTION

To produce liquid helium basically it is essential to separate helium from atmospheric air and cooling it down to 4 K for achieving condensation. The liquid helium at 4 K has been collected a Dewar flask. These collection vessels are vacuum jacketed to separate the vessel storing liquid helium from meteorological conditions. The space between the radiation shield and vacuum vessel is evacuated in order to reduce the convection thermal load and several layers of insulation has been used to bring down the radiation thermal load coming from the vacuum jacket (at 300 K) to cryogen vessel (at 4 K).

In this research work, the commercially available GM cryocooler has been used and a heat exchanger wounded over the cryocooler stages to effectively produce liquid helium at 4 K. The estimated refrigeration capacity at 4.2 K is 1.5 W. The GM cryocooler system composed of Helium flex lines, Compressor package and cold head. The collection vessel has been attached on the cold head (second stage) of the GM cryocooler. The helium gas when comes in contact with heat exchanger it begins to liquefy. The liquefied helium drops down from the heat exchanger into the collection vessel. The phase change would usually reduce the pressure inside the vessel, but the regulator flow allows more helium gas to

come into the collection vessel to preserve the pressure at the predefined level. The rate of flow of helium gas into the vessel is monitored by the rate of liquefaction inside the collection vessel.

The helium liquefaction can be achieved by the evacuation of the Dewar flask by using a turbo molecular pump till required vacuum pressure has been achieved in vacuum pressure gauge. By switching on the GM cryocooler and note down the temperature reduction every 10 minutes till the cold head reaches a temperature of 2 K - 3 K. After achieving the required temperature, the inlet to gas from the helium cylinder has been opened the liquid helium starts collecting in the collection vessel. The thermoacoustic oscillations have been observed in pressure gauge when liquid helium comes in contact with the end of pressure gauge, this gives the indication that the collection vessel is filled with liquid helium.

Figure1 illustrates the helium liquefaction experimentation setup. The helium gas which is at room temperature has been drawn from a standard helium gas cylinder through a pressure regulator. Rotameter type of flow meter used to check the flow of helium gas. The shut off ball valve after the flow meter used to regulate the flow of helium gas into the system.

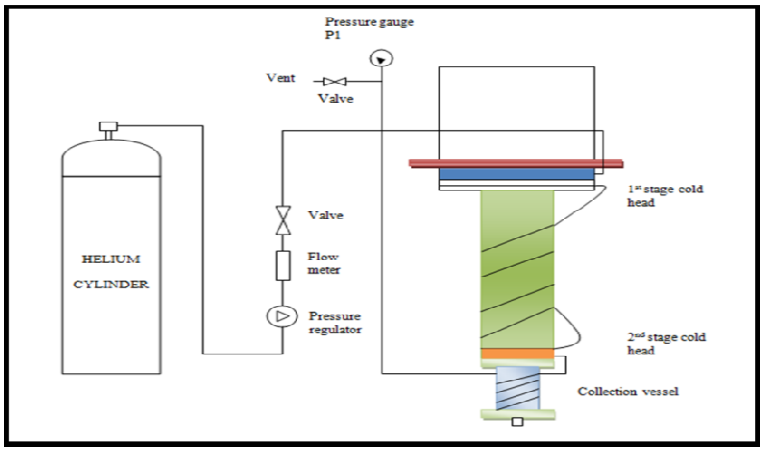

Figure 1: Helium Liquefaction Setup

Small scale helium liquefaction system has been successfully developed by using GM cryocooler. This demonstrate the liquefaction with a commercial two-stage GM cryocooler, which delivers a cooling power of 1.5 W at 4.2 K at its second stage cold head and a cooling power of 30 W is available at 35 K in the first stage. The incoming helium gas is pre-cooled at the first stage cold head and subsequently is passed on to second stage cold head through the specially designed heat exchanger. The collection of liquid helium has been monitored by thermo acoustic oscillation in the vapor pressure gauge connected outside. The setup comprises Gifford-McMahon cryocooler stages wounded with Copper heat exchanger to increase the rate of heat transfer. The collection vessel has been employed for a known volume of 100 cm^3collection vessel made of Copper. The collection vessel has two openings: one for the inlet of liquid helium and other for the connection of pressure gauge to monitor the thermoacoustic oscillations.

The precooling of incoming helium gas is very important in liquefaction process, this work is effectively accomplished by spirally wounded copper tube around cryocooler stages. At first helium gas passes through the spirally wounded heat exchanger around first stage cold head. The dimension as well as the number of turns of copper tube has to be optimized in order to achieve a minimum pressure drop and also to ensure precooling of incoming helium gas to a temperature equivalent to temperature of the first stage. It consist of a copper capillary with an outer diameter of 3 mm and a wall width measuring 0.25 mm, soft soldered to a thin copper sheet of thickness 0.2 mm and is fixed to the first stage.

The above mentioned copper capillary is also used as heat exchangers, in order to ensure unstable flow of helium gas to achieve better radial heat transfer over the capillary wall.

The piping between the heat exchangers of the first and second stage are made up of narrow walled stainless steel tubes having the same diameter as that of copper tube. Since the greater amount of enthalpy is removed at the first stage, helium gets liquefied in the heat exchanger that is mounted on the second stage due to passage of gas over the cold surface area. Figure 2 indicates heat exchanger of second stage cold head and mounted collection vessel on second stage. The liquid helium leaving the heat exchanger enters the collection vessel. The collection vessel is thermally connected to the second stage of the cryocooler.

3. MONITORING LIQUEFACTION USING VAPOR PRESSURE GAUGE

Figure 2 depicts a pressure gauge arrangement to monitor the pressure inside collection vessel and also thermoacoustic oscillations.

Figure 2: Pressure Gauge Arrangement

Figure 3 depicts the thermoacoustic oscillations that have been observed in a vapor pressure gauge. When liquid helium starts collecting in the collection vessel, thermoacoustic oscillations have been produced. The observed frequency is the low, when liquid helium touches the other end of the capillary tube. On the other side, when helium liquid is released to atmospheric conditions it gets condensed in the surrounding air. After emptying the collection vessel the valve is closed completely. It results in high frequency of oscillation in the pressure gauge due to entry of warm helium gas into to the collection vessel due to high pressure variations.

Figure 3: Thermoacoustic Oscillation

The following are the steps involved in experimentation:

Step 1: Switch on the chiller unit and turbo molecular pump for cooling of water and evacuation process inside Dewar. After some time, the temperature of a chiller unit decreases to 11^0 C from room temperature. The evacuation process results in the decrease in vacuum pressure from room pressure to a pressure of 10^{-3} mbar.

Step 2: After achieving this temperature (chiller unit) and vacuum pressure, switch on the cryocooler device.

Step 3: The liquid helium outlet is closed by using a suitable valve. The gas inlet of collection vessel is connected to an external helium gas cylinder fitted with pressure regulator through a flow meter. The inlet gas pressure is adjusted such that positive pressure head exist in the system.

Step 4: By switching on the cryocooler device results in the gradual cooling of the first and second stages and vessel. This decrease in temperature readings have been noted by using a temperature controller device after every 10 minutes. During the cool down process, the system has to be ensured that the inlet pressure of helium gas from the cylinder through flow meter is always positive and exit to liquid helium is closed with suitable arrangement.

Step 5: After initial cool down (temperature of 4 K), which occurs after nearly 3 to 5 hours, liquid helium starts to collect in the collection vessel. When the liquid helium level touches the end of the capillary tube, low frequency thermoacoustic oscillations have been observed spontaneously.

Step 6: The outlet vent valve is opened, and then liquefied helium is now vented to recovery. Cold helium gas passes out through the stainless steel tube and this in turn condenses with the ambient air on the outside of this pipe. After the release of cold helium, if the outlet vent is closed, it results in high frequency thermoacoustic oscillation. The experimentation is also carried out by inverting the Dewar flask on a suitable arrangement with a similar procedure.

This review paper gives the idea about the experimental approach and the method of performance assessment of G – M cryocooler, which has been encouraged by the Center for Cryogenic Technology, Indian Institute of Science, Bangalore.

4. CONCLUSIONS

In this research work, an attempt has been made to accomplish the performance of small- scale Gifford – Mcmahon cryocooler wherein series of experiments have been carried out at Center for Cryogenic Technology, Indian Institute of Science, Bengaluru, India.

REFERENCES

1. *W. E Gifford, R. C. Longsworth, Pulse Tube Refrigeration, Trans. ASME: Jl. of Engg. for Industry, 86 (1964), pp. 264-268.*
2. *E. I. Mikulin, A. A. Tarasov, M. P. Shkrebyonock, Low temperature expansion Pulse Tubes, Adv. in Cryog. Engg, 29, (1984), pp. 629-637.*
3. *S. Kasthurirengan, G. Srinivasa, G. S. Karthik, D. S. Nadig, U. Behera, K. A. Shafi, Int. Jof Heat and Mass Transfer 52, 2009, pp. 986–995.*
4. *M. A. Green, The liquefaction of hydrogen and helium using small Cryocoolers, LBNL-62458, 2007.*
5. *C Wang, Efficient helium recondensing using a 4 K pulse tube Cryocooler, Cryogenics, 45 (2006), pp. 719-724.*

6. *A. Hofmann, Device for recondensation by means of a cryogenerator, of low boiling gases evaporating from a liquid gas container, US Patent no. 6990818, 2006.*
7. *TallakiMorie, Taisuke Shiraishi and Mingyrao Xu, "Experimental investigation of cooling capacity of 4K GM cryocoolers in magnetic fields, Physics Procedia, Vol. 67, 2015, pp. 474-478.*
8. *T. Satoh, A. Onishi, I. Umehara, Y. Adachi, K. Sato and E. J. Minehara, "A Gifford-McMahon cycle Cryocooler below 2K", Springerlink, Cryocoolers 11, pp. 381-386.*
9. *T. Satoh, A. Onishi, Rui Li, H. Asami and Y. Kanawaza, "Development of 1.5 W 4K GM Cryocooler with magnetic regenerator materials", Advances in Cryogenic Engineering, pp. 1631-1637.*
10. *Kumar, R. S. Latent Heat Storage Material Evaluation Base On Ahp And Topsis For Low Temperature Solar Heating Applications.*
11. *I. Takashi, N. Masachi, N. Kouki and Y. Hideto, "Development of a 2W class 4K GM cycle cryocooler", Springerlink, Cryocoolers 9, pp. 617-626.*
12. *M. Xu, Q. Bao, A. Tsuchiya and R. Li, "Development of compact 2K GM cryocoolers", Physics Procedia, Vol. 67, 2015, pp. 491-496.*
13. *Dong Xu, Linghui Gong, Laifeng Li, Xiangdong Xu, Huiming Liu, Rongjin Huang, Experimental investigation and optimization of small-scale helium liquefaction with multi-cryocoolers, Cryogenics, Vol. 69, July 2015, pp. 10–17.*
14. *The liquefaction of helium by an adiabatic method, Papers of P. L. Kapitza, Vol.1,1964, pp. 485–502.*
15. *Owaid, A. I., Tariq, M., Issa, H., Sabeeh, H., & Ali, M. The Heat Losses Experimentally In The Evacuated Tubes Solar Collector System In Baghdad-Iraq Climate.*
16. *R. Kneuer, K. Petersen, A. Stephan, Automatic multi-range helium-liquefaction plant, Cryogenics, Vol. 20, Issue 3, March 1980, pp. 129–132.*
17. *Akihiro Nakano, Tetsuhiko Maeda, Hiroshi Ito, Masao Masuda, Yoshiaki Kawakami, Atsushi Kato, Manabu Tange, Toru Takahashi, Masahiro Matsuo, Small-scale hydrogen liquefaction with a two-stage Gifford–McMahon cycle refrigerator, Adv. In Cryogenics Engineering, Vol. 35, Issue 17, September 2010, pp. 9088–9094.*
18. *T. B. He and Y. L. Ju, Performance improvement of nitrogen expansion liquefaction process for small-scale LNG plant, Cryogenics, Vol. 61, 2014, pp.111-119.*
19. *Mahrous, A. (2013). Thermal performance of PCM based heat sinks. Int J Mech Eng, 2(4).*
20. *P. Schmidt-Wellenburg and O. Zimmer, Helium liquefaction with a commercial 4 K Gifford-McMahon cryocooler, Cryogenics, Volume 46, Issue 11, pp. 799-803, 2006.*